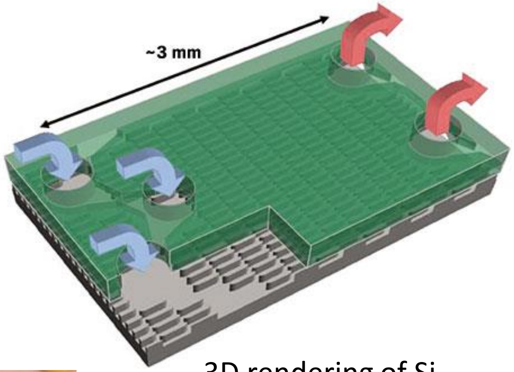
Reliability of Microchannel Coolers for High Heat Flux Power Electronics Applications

D. Squiller, I. Movius, S. Dessiatoun, R. Mandel, M. Ohadi, P. McCluskey
CALCE/Dept. of Mechanical Engineering
A. James Clark School of Engineering
University of Maryland, College Park
(301) 405-0279
mcclupa@umd.edu

Manifold-Microchannel Coolers for High Heat Flux Power Electronics

- Manifold-Microchannel coolers can be embedded directly into the substrate or chip to provide localized heat removal at high volumetric rates[1] from the backside of active ICs and power electronic devices.
- These coolers take many forms. For example single vs. two-phase, silicon vs. ceramic substrates and different alloys, filter size, working fluid, fluid velocity, and temperature.
- They are used to overcome thermal limits that can cause power electronic devices to operate at voltages and currents below their inherent electrical limits.
- No "one-size-fits-all" reliability solution.



3D rendering of Si microchannel cooler[2]

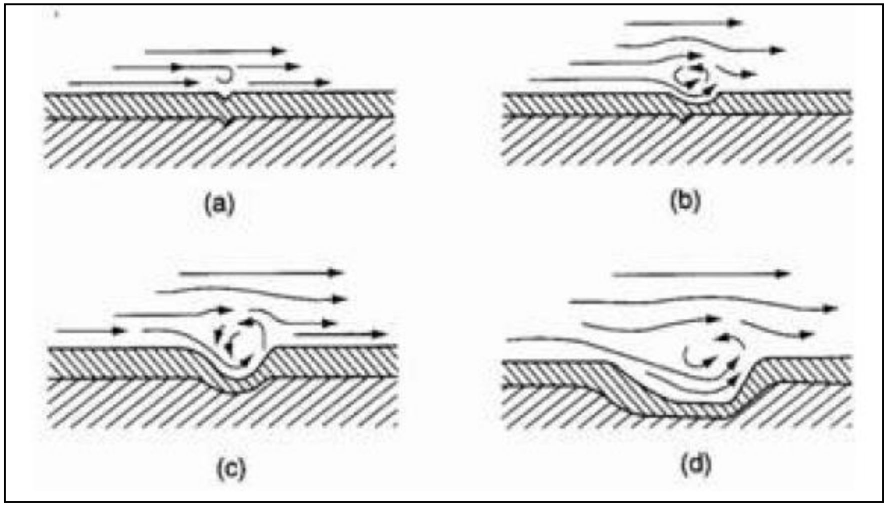
Rogers Corp. curamik ®Coolers. [3]

Reliability Aspects of MCCs

Erosion: Entrained particles impinge on the walls altering channel geometry and generating particulates.

Corrosion: Relatively uniform dissolution of material into solution, and formation of brittle oxide layers.

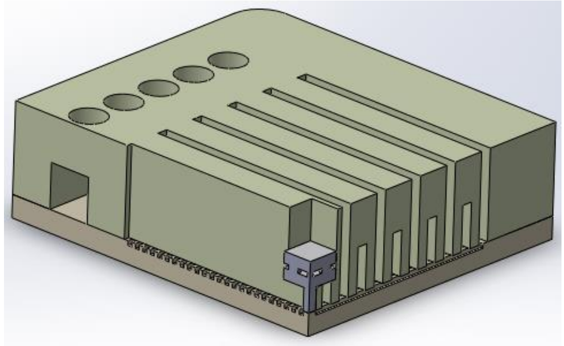
Clogging/fouling: Entrained particles become attracted to channel surfaces. Layers of particles form eventually leading to full blockage.

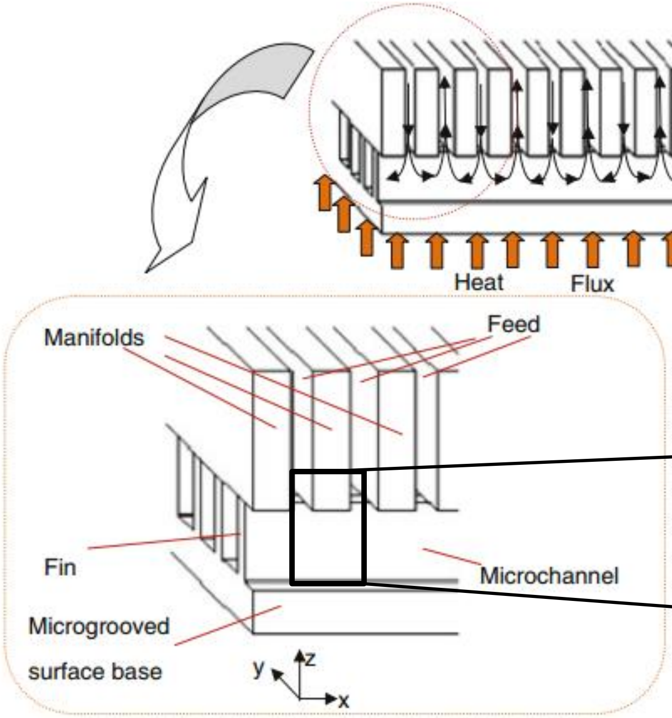


Erosion-corrosion phenomena [5]

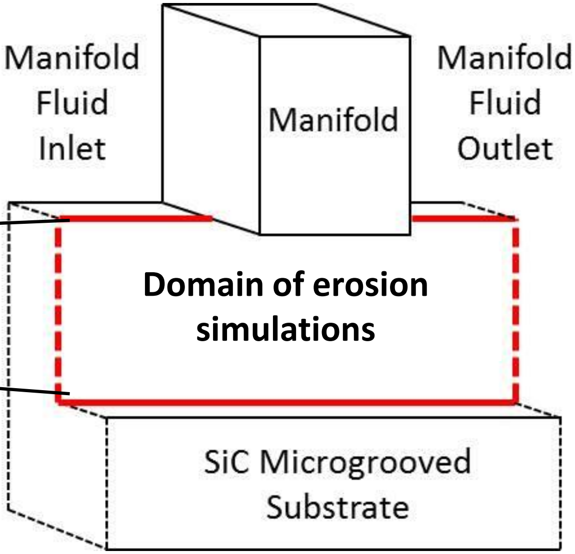
Specific Design Studied

- Force Fed Microchannel Heat Exchanger (FFMHX) design[4]. Series of parallel microchannels with perpendicularly oriented manifold to distribute flow.
- Micro-grooved surface is manufactured in single-crystal Silicon Carbide (SiC).



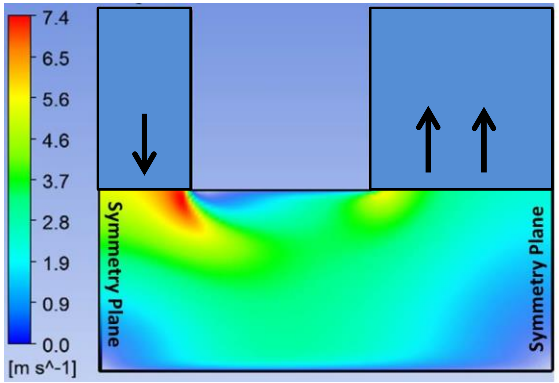


Design of FFMHX with integrated manifold[4]

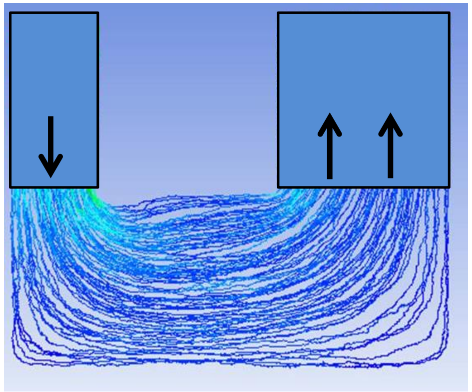


CFD Erosion Simulations: Introduction

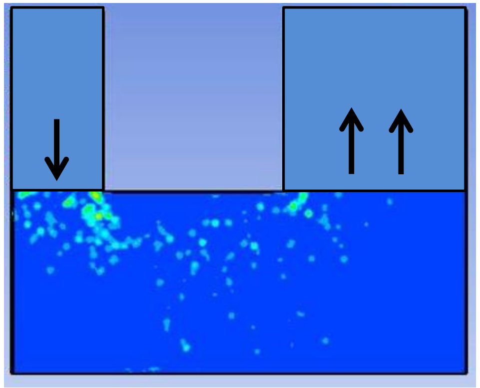
- Widely used in the Oil & Gas industry [10-12].
- Conducted in three primary steps:
  1) Numerically compute flow field
  2) Calculate particle trajectories
  3) Model particle-wall interactions (erosion equation)



Computation of flow field using commercial CFD Code



Coupling particle trajectories to flow field



Generation of erosion contours based on particle-wall interaction equation

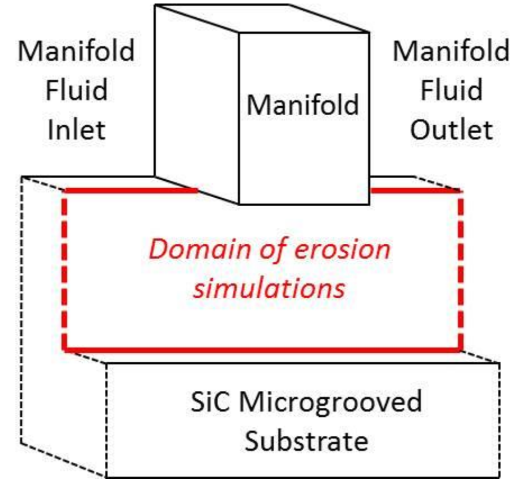
Particle Erosion Modeling

Particle erosion models of **single-crystal silicon** were used for preliminary modeling purposes. An inlet velocity of 4 m/s (single-phase fluid) was assumed to determine to effect of particle size and concentration on the erosion rate.

$$\Delta W = A(V sin(\theta) - V_o)^n (D - D_o)^m$$

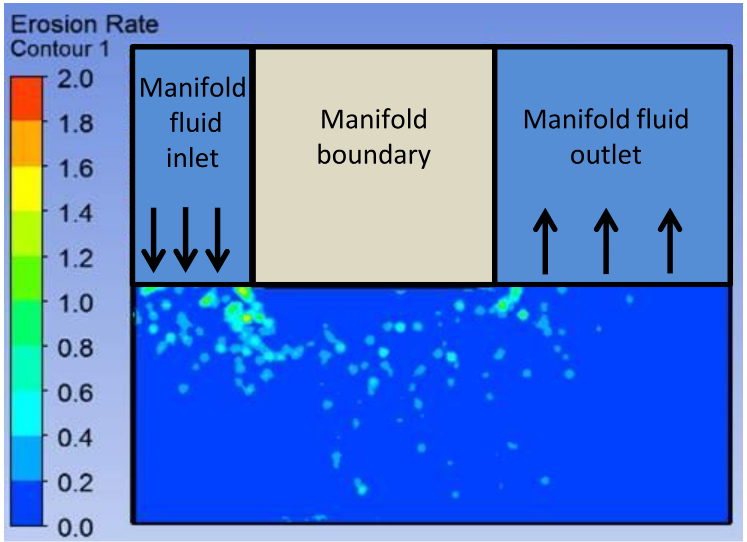
V_0 and D_0 assumed to be equal to 0.

Routbort and Scattergood[13-15]



Operational Condition

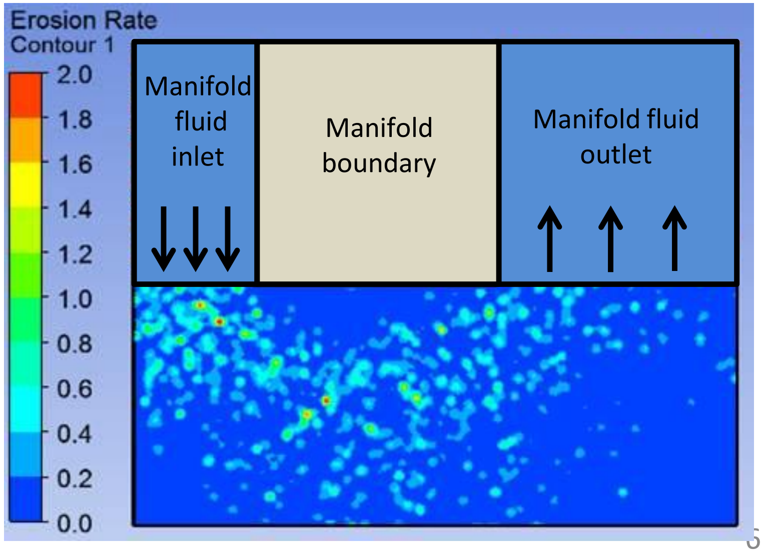
100 nm particles



Units in μm/yr.

Accelerated Condition

1μm particles 1%



Challenges in Modeling Erosion using CFD

Particle erosion models developed using "sandblasting" tests.

- Significantly higher velocities and particle sizes than those present in microchannel cooling loops. Slurry erosion tests seldom include particles in the single-micron/submicron regime.
- Effect of particle-induced "squeeze-film" is neglected as sandblasting tests are performed in air.
- Difficult to capture particle-induced viscous dampening as particle approaches wall[16]. Requires two-way particle-fluid coupling. Very computationally expensive, difficult to achieve convergence.

Can erosion models calibrated for larger particles and velocities be used to predict erosion in microchannel coolers?

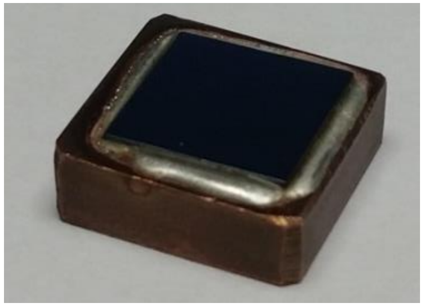
Literature suggests the existence of threshold particle and velocities under which no erosion will occur. Will this hold true over 10^2, 10^3… 10^6 hours?

Slurry Erosion Test Apparatus

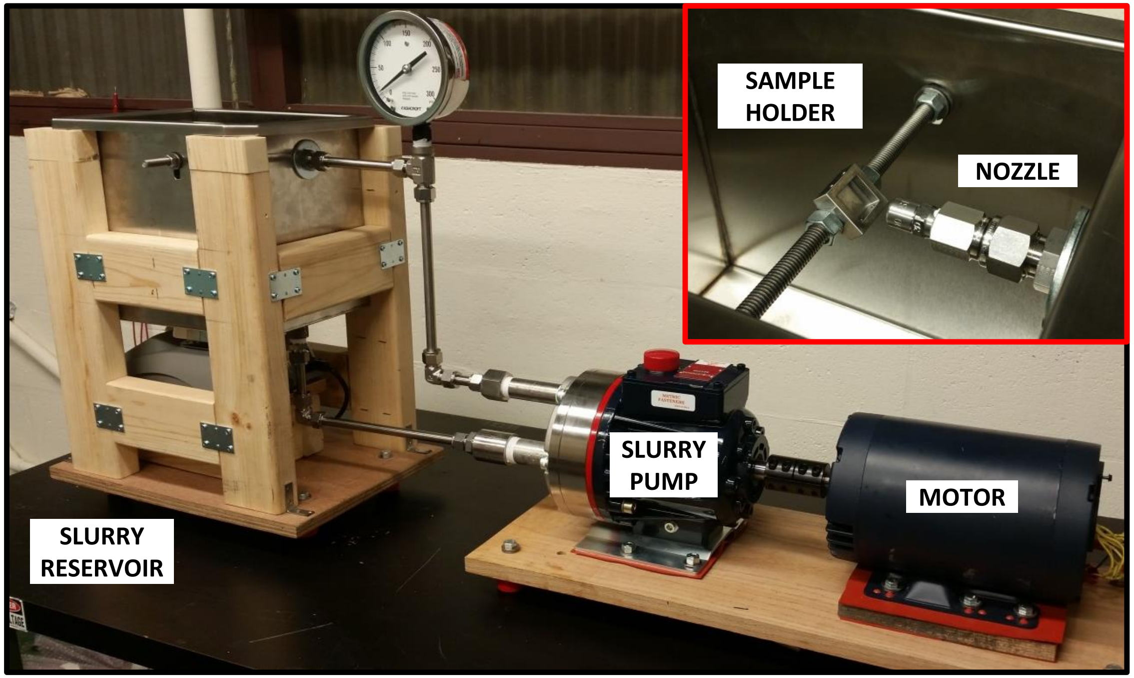
- Gain insight into the removal mechanism of the various materials involved in microchannel coolers.
- Determine and calibrate model to predict erosion in microchannel coolers. Determine threshold velocities and particle diameters.

<u>Factor Ranges to be Considered</u>

Velocities: 5 – 60 m/s
Particle sizes: 0.1 – 25 µm
Particle conc: 0 - 5 (% mass)
Impingement angles: 0 - 90 °
Particulate: SiC, Alumina, Steel

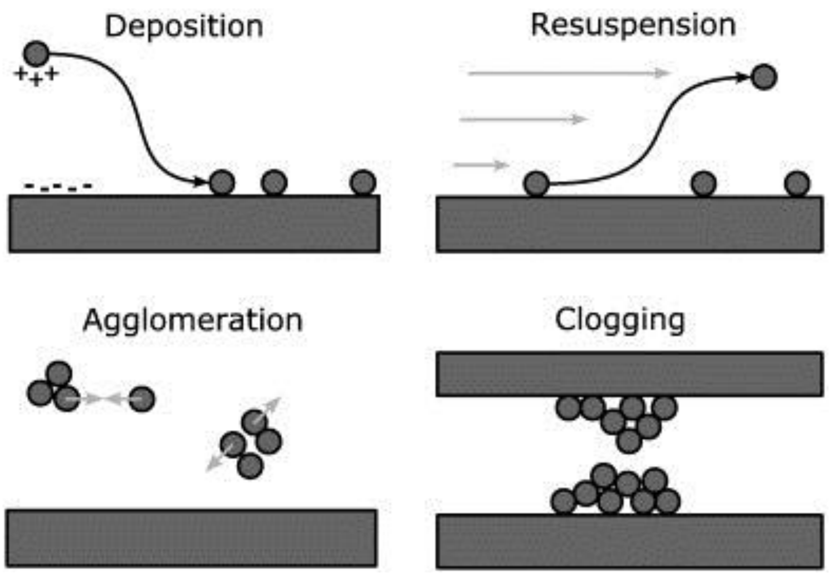


Polished Si soldered to Cu

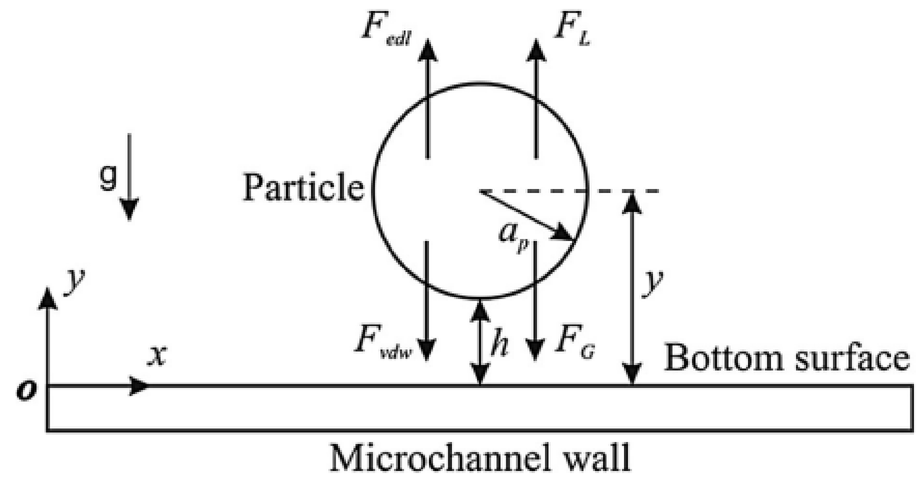


<u>TESTING IN PROGRESS</u>

Fundamentals of Fouling/Clogging



Clogging Mechanisms[16]



Forces involved in particulate clogging [17]

Van Der Waals Force (F_{vdw}):
Attractive force between particles or particle to wall. Largely a function of pH and electrolyte concentration.

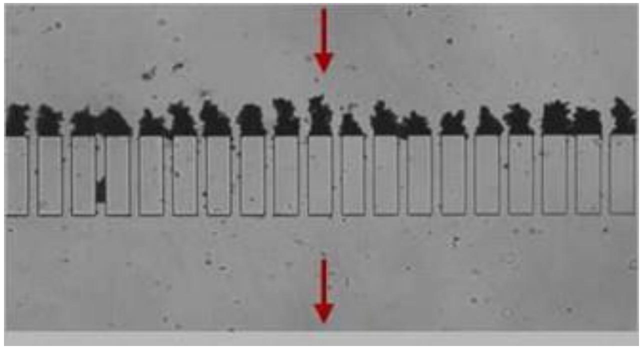
Hydrodynamic Forces incl. Gravity (F_L, F_G):
Responsible for bringing particle close to the wall or lifting particles away from the wall.

Electric Double Layer Force (F_{edl}):
Repulsion force due to the surface charges on the particles and wall. Largely a function of particle size and zeta potential.

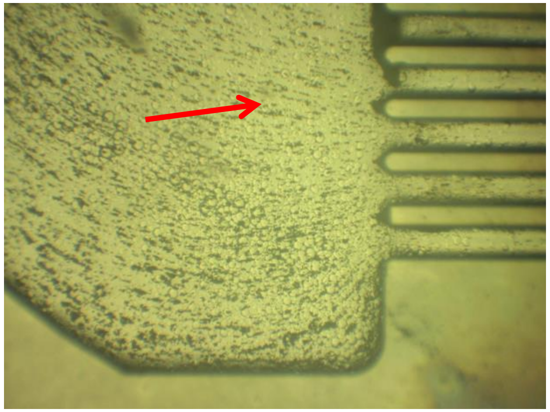
Fouling/Clogging phenomena occurs when net attractive forces overcome net repulsive forces.

Clogging of microchannels

- Previous studies have shown that particulate build-up and clogging **within** the microchannels are not likely to occur.



Particulate formations on the fin surfaces connect to block the channel entrance[18]

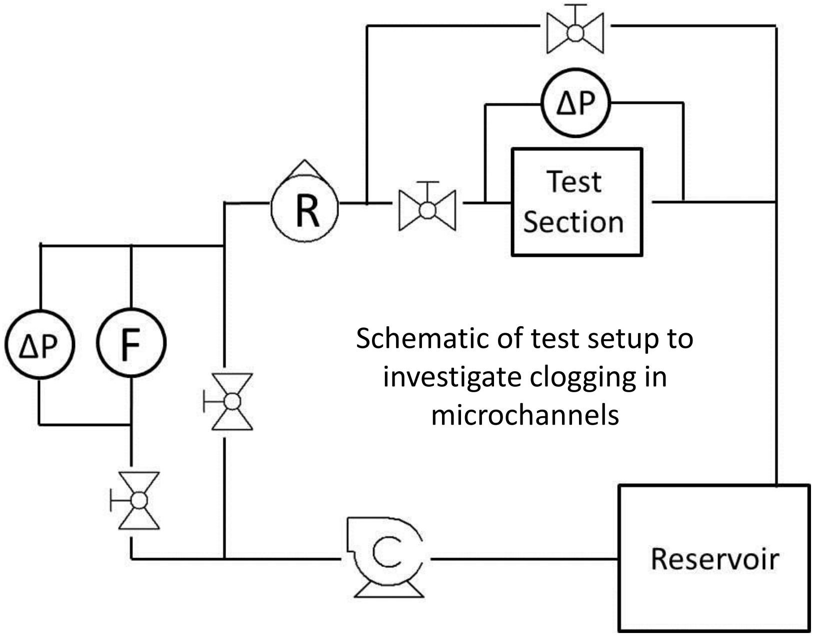


Fouling occurs in the manifold while clogging occurs at the channel entrances [19]

- Major location of fouling is within **header/manifold** region due to the lower shear stress and abrupt changes in flow direction as fluid enters channels.
- One of the best ways to control particle agglomeration and build-up is by adjusting pH and very stringent particle filtering controls (e.g. less than 0.5μm).

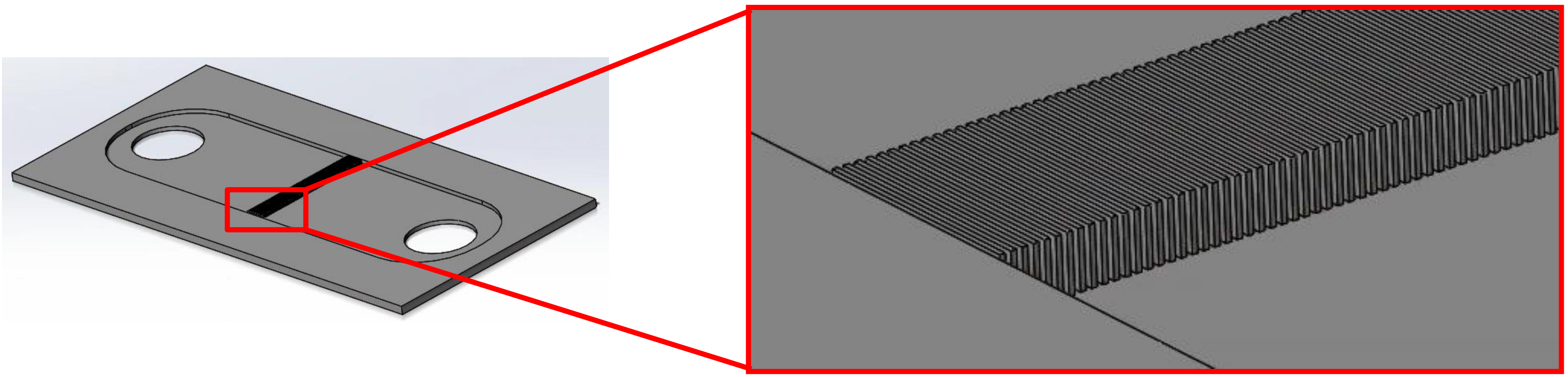
Adjusting pH or using a small filter may not be ideal for the application

Experimental Clogging Test Setup

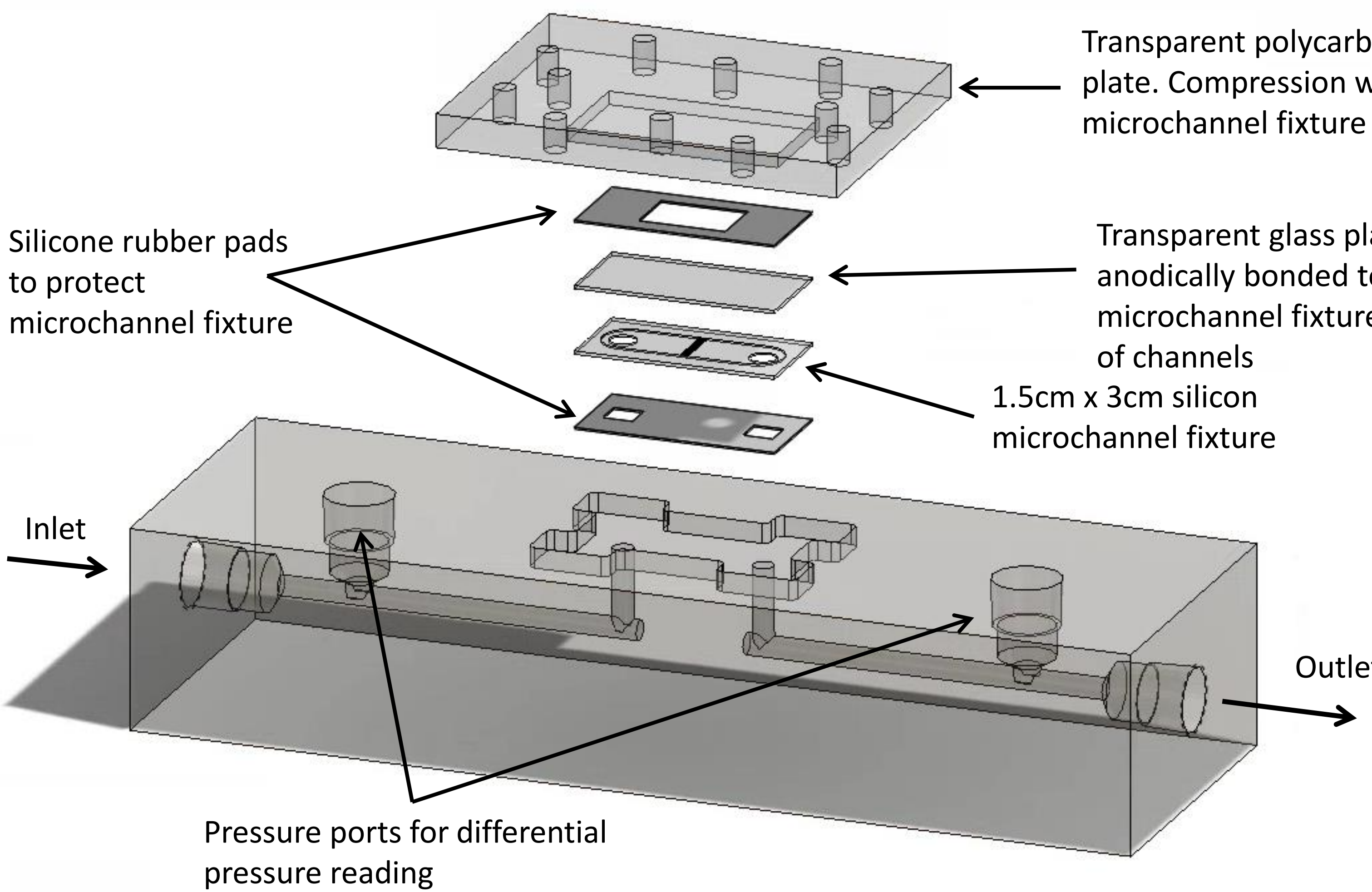


Schematic of test setup to investigate clogging in microchannels

- Investigating major factors contributing to clogging of microchannel coolers including particle size, concentration, pH, velocity, particulate material.
- Identify how various manifold designs impact clogging



Design of Clogging Test Section



Concluding Remarks

Particle Erosion:

- Likely to be a concern for Si microchannels after 10^5 hours of operation.
- Extension of model to SiC with small particles and low flow rates must be validated.
- Slurry erosion test apparatus constructed to determine threshold particle size and velocities for microchannel cooler materials.
- Will gain insight into material removal mechanisms and establish most appropriate erosion model for microchannel coolers.

Clogging/Fouling Experiment:

- Test setup designed to investigate major factors contributing to clogging/fouling in microchannel coolers.
- Study how different manifold structures affect propensity for clogging.

Designing reliability into microchannel designs

Acknowledgments

The authors would like to thank Prof. Avram Bar-Cohen, Dr. Daniel Green, Dr. Kaiser Matin, Dr. Paul Boudreaux, and Dr. Joseph Maurer for their technical contributions to this work and to thank and acknowledge DARPA for sponsoring this research under Cooperative Agreement No. HR0011-13-2-0012. In addition, the authors would like to acknowledge the technical contributions of Mr. Ian Movius.

References

[1] Broad Agency Announcement Intrachip/Interchip Enhanced Cooling Fundamentals (ICECool Fundamentals) Microsystems Technology Office.

[2] Colgan, E.G.; Furman, B.; Gaynes, M.; Graham, W.S.; LaBianca, N.C.; Magerlein, J.H.; Polastre, R.J.; Rothwell, Mary Beth; Bezama, R.J.; Choudhary, R.; Marston, K.C.; Toy, H.; Wakil, J.; Zitz, J.A.; Schmidt, R.R., "A Practical Implementation of Silicon Microchannel Coolers for High Power Chips," *Components and Packaging Technologies, IEEE Transactions on* , vol.30, no.2, pp.218,225, June 2007

[3] www.rogerscorp.com, curamik CoolPerformance Coolers

[4] M. Ohadi, K. Choo, S. Dessiatoun and E. Cetegen. Next Generation Microchannel Heat Exchangers. Springer New York Heidelberg Dordrecht London, 2013, pp. 33-64.

[5] http://www.corrosionlab.com/papers/erosion-corrosion/erosion-corrosion.htm

[6] Park, Jeong-Yong, et al. "Long-term corrosion behavior of CVD SiC in 360° C water and 400° C steam." *Journal of Nuclear Materials* 443.1 (2013): 603-607.

[7] Barringer, E., et al. "Corrosion of CVD silicon carbide in 500 C supercritical water." *Journal of the American Ceramic Society* 90.1 (2007): 315-318.

[8] Tan, L., T. R. Allen, and E. Barringer. "Effect of microstructure on the corrosion of CVD-SiC exposed to supercritical water." *Journal of Nuclear Materials* 394.1 (2009): 95-101.

[9] Henager Jr, Charles H., et al. "Pitting corrosion in CVD SiC at 300° C in deoxygenated high-purity water." *Journal of Nuclear Materials* 378.1 (2008): 9-16.

[10] Forder, Alister, Martin Thew, and David Harrison. "A numerical investigation of solid particle erosion experienced within oilfield control valves." *Wear* 216.2 (1998): 184-193.

[11] Zhang, Yongli. *Application and improvement of computational fluid dynamics(CFD) in solid particle erosion modeling*. Dissertation. The University of Tulsa.

[12] Chen, Xianghui, Brenton S. McLaury, and Siamack A. Shirazi. "Application and experimental validation of a computational fluid dynamics (CFD)-based erosion prediction model in elbows and plugged tees." *Computers & Fluids* 33.10 (2004): 1251-1272.

[13] Routbort, J. L., R. O. Scattergood, and E. W. Kay. "Erosion of silicon single crystals." *Journal of the American Ceramic Society* 63.11-12 (1980): 635-640.

[14] Scattergood, Ronald O., and Jules L. Routbort. "Velocity Exponent in Solid-Particle Erosion of Silicon." *Journal of the American Ceramic Society* 66.10 (1983): c184-c186.

[15] Scattergood, R. O., and J. L. Routbort. "Velocity and size dependences of the erosion rate in silicon." *Wear* 67.2 (1981): 227-232.

[16] Henry, Christophe, Jean-Pierre Minier, and Grégory Lefèvre. "Towards a description of particulate fouling: from single particle deposition to clogging."*Advances in colloid and interface science* 185 (2012): 34-76.

[17] Perry, Jeffrey L., and Satish G. Kandlikar. "Fouling and its mitigation in silicon microchannels used for IC chip cooling." *Microfluidics and Nanofluidics* 5.3 (2008): 357-371.

[18] Bacchin, Patrice, et al. "Clogging of microporous channels networks: role of connectivity and tortuosity." *Microfluidics and nanofluidics* 17.1 (2014): 85-96.

[19] Perry, Jeffrey L. *Fouling in silicon microchannel designs used for IC chip cooling and its mitigation*. ProQuest, 2007.